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Reservoir parameters of lithostratigraphic successions of the lower Paleozoic strata in the Polish part of the Baltic region based on laboratory studies and well logs

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For lithostratigraphic successions of the lower Paleozoic strata in the Polish part of the Baltic Sea between the Słupsk Block and Courland Block, assessment of petrophysical properties was carried out with the use of mercury porosimetry and well logging results. The porosimetric measurements allowed to determine critical rock parameters and to distinguish genetic types of reservoirs. To complete the information on reservoir parameters, available well logs were used. The logs allowed identification of Cambrian strata in boreholes and the distinguishing of several lithostratigraphical units. Results of the porosimetric measurements demonstrated the strongly heterogeneous character of the pore space in the Cambrian rocks, with generally very weak reservoir properties. Fractured and porous-fractured rock space is a principal feature here. Well log anomalies confirmed the diversified lithological development of the Cambrian profile and the somewhat better reservoir parameters of rocks of the *Paradoxides paradoxissimus* Superzone and the shaly character of the *Eccaparadoxides oelandicus* Superzone. From the point of view of volumes of potential hydrocarbon accumulations, the capacity of the Cambrian deposits is low, but this is a basic feature of reservoir rocks with fractured and fractured-porous space.

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Key words: Baltic region, lower Paleozoic, petrophysical parameters, pore space, porosimetry, well logging.

INTRODUCTION

Determination of quantitative petrophysical parameters of reservoir horizons in an oil- and gas-bearing formation is a key element for defining migration and accumulation processes in a petroleum system. This requires quantitative determination of physical parameters of the pore space, principally based on analysis of direct laboratory measurements and the results of well logging. By this means, filtration space of distinguished successions, formations, and lithostratigraphic horizons for potential hydrocarbon migration and accumulation can be defined.

The main purpose of the paper is the assessment of the petrophysical parameters of the lithostratigraphic successions of lower Paleozoic strata in the Polish part of the Baltic Sea between Koszalin and Kuźnica Fault zones (Fig. 1). The geological setting of this region has been discussed in detail by Karnkowski *et al*. (2010), Modliński and Podhalańska (2010) and Pokorski (2010) in this volume.

METHODOLOGY

For evaluation of the rock pore space, porosimetric studies are of great importance.

Capillary pressure measurements with the use of the mercury porosimetry allow one to identify potential reservoir rocks, evaluate their quality and expected saturation with reservoir fluids. The essence of this method is based on the assumption that capillary pressures result from the interaction of forces

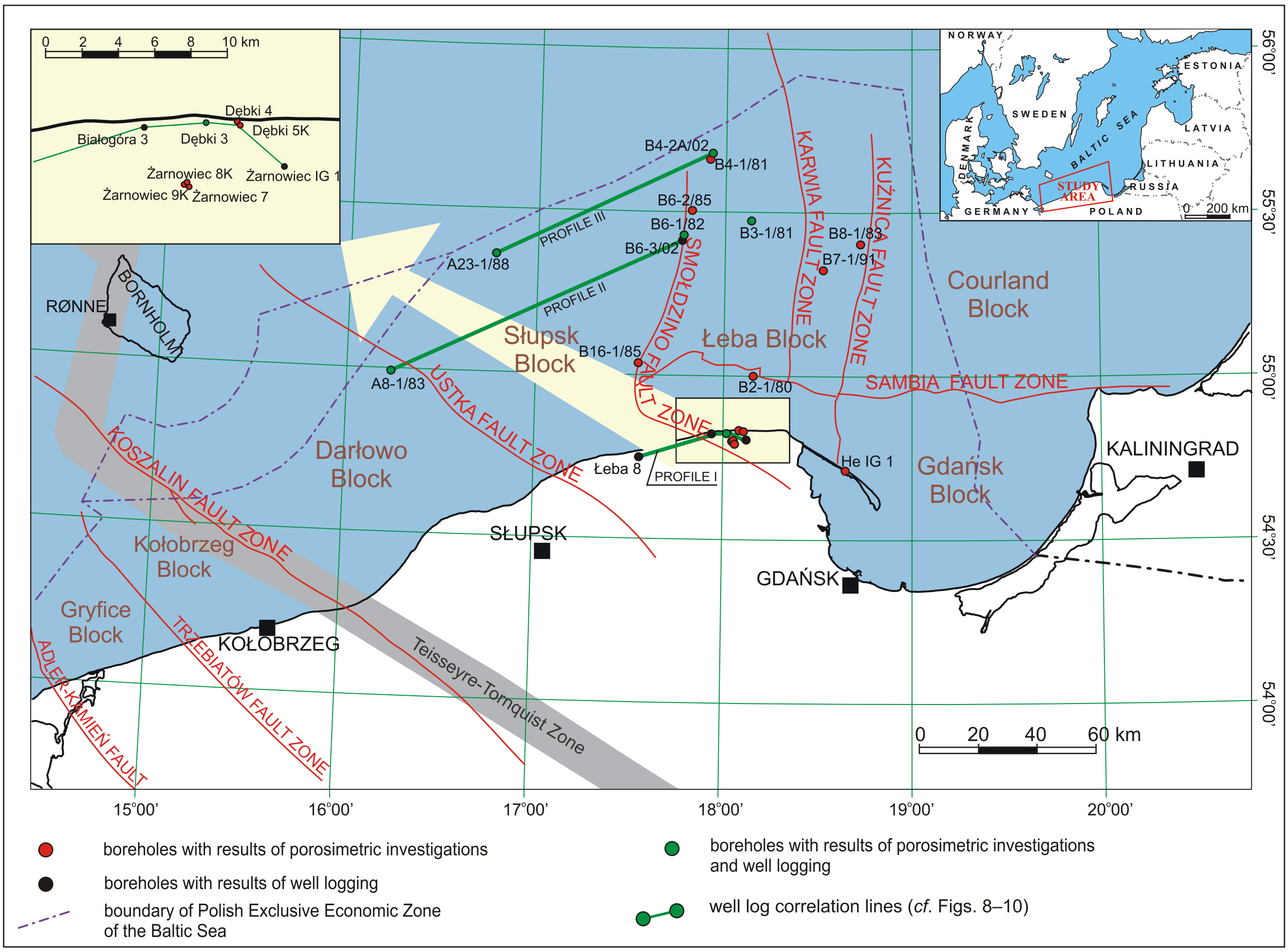


Fig. 1. Sketch map of the Polish part of the Baltic region and location of boreholes and correlation lines analysed

Fault system after Pokorski (2010)

acting within the fluid (i.e., cohesion) and forces between the fluids saturating the pore space and the rock framework (i.e., adhesion). The porosimetric method is based on intrusion of mercury (being a nonwetting "working" liquid that does not react with the rock framework), which simulates the pre-migration characteristics of potential wettability of the reservoir rock (Vavra *et al.*, 1992). This allows one to carry out comprehensive analysis of values of particular petrophysical parameters that provide the basis for classification, and qualitative and quantitative characterization, of potential reservoir and sealing rocks (Washburn, 1921; Vavra *et al.*, 1992; Tiab and Donaldson, 1996). This means not only that a void-ratio value qualifies rock as a potential reservoir of a definite class, but also other parameters of this space are decisive, mostly the pore diameter size and distribution, fracture width, total pore area, and the geometry of distribution of pores *versus* their diameters, within the range of the supercapillary, capillary and subcapillary spaces (Wardlaw *et al.*, 1976; Burzewski *et al.*, 2001; Słupczyński *et al.*, 2001; Kuśmierek and Semyrka, 2003; Semyrka *et al.*, 2008).

The analysis presented concerns the physical characterization of the pore space in the reservoir rocks through determination of the following parameters: rock density, effective and dynamic porosities, pore space geometry, average pore diameter, and total pore area (Smoleńska *et al.*, 1995; Smoleńska and Semyrka, 1996; Bachleda-Curuś and Semyrka, 1997; Such, 2002).

Evaluation of potential reservoir and sealing rocks is based on quantitative analysis of a number of parameters controlling hydrocarbon saturation and flow in the pore space (Perrodon, 1980; Plewa and Plewa, 1992). Physical models of homogeneous-fluid flow in porous media are determined by ranges of critical pore diameters, which enable one to distinguish five basic capacity classes: very low, low, moderate, high, and very high capacities (Słupczyński *et al.*, 2001; Kuśmierek and Semyrka, 2003; Semyrka *et al.*, 2008).

Quantitative analysis of a capillary pressure curve makes also possible the determination of the reservoir capacity of an analysed sample, and to distinguish genetic types of the voids based on the relationship between intergranular pores and microfractures: porous, porous-fractured, and fractured reservoirs (Semyrka and Szybiński, 1976; Strzetelski, 1977, 1980; Górecki and Strzetelski, 1984; Krach and Semyrka, 1984; Semyrka *et al.*, 2008).

The nature of the porosimetric method determines that the pore space evaluation refers to the supercapillary, capillary, and subcapillary spaces in which the whole process of migration and accumulation of reservoir fluids takes place. On the grounds of this division, gas filtration space was distinguished at pore diameters d >0.1 μm and oil filtration space at d >1 μm, which then allowed us to define dynamic porosities for gas and for oil (Burzewski *et al*., 2001; Semyrka *et al*., 2008).

The porosimetric measurements were carried out with application of the *AutoPore II 9220* mercury porosimeter at the Department of Fossil Fuels, AGH University of Science and Technology, on well cuttings delivered by the Polish Oil and Gas Company from the onshore boreholes and by LOTOS "Petrobaltic" S.A. from the offshore area.

Laboratory analyses of rock samples represent a direct way to acquire information on petrophysical parameters. Results obtained, however, are not always representative of the strata under study, due to small sample sizes, non-representative sampling of the mostly heterogeneous rock, and not maintaining conditions preexisting in the undisturbed rock mass, as well as due to different scales of processes that constitute the basis for the measurement of a given parameter. Well logging can bridge the gaps in the evaluation of the rock parameters based on laboratory studies. Logs provide continuous information as a function of depth along a full geological profile but logs are only an indirect means of data acquisition. Combining results of laboratory studies and well logging represents the best way to gain reliable information.

To complete the information on reservoir parameters of Paleozoic rocks in the study area, available well logs were used. Gamma-Ray (GR), comprising measurement of the natural radioactivity of rocks in order to determine the clay content, was selected as belonging to the most informative group, as well as electric resistivity logs (at least two logs, for shallow and deep radial investigations). Resistivity logs were used to check for the occurrence of an invaded zone in the rock and the possibility of fluid movement in the rock pore space, and to assess the relationship between the resistivity in the zone close to the borehole and in the distant zone, away from the invasion extent. Neutron logs were also used in order to obtain information on neutron porosity, NPHI (NEGR), as well as interval transit time measurements (DTM) during acoustic logging, and bulk density determinations, RHOB, through density logs. Shapes and sizes of anomalies on selected logs were analysed to identify selected Cambrian horizons. Lithostratigraphic horizons were distinguished and correlation of the strata distinguished along selected profiles was performed (Fig. 1). Detailed analysis of the anomalies on the logs has indicated whether the rocks are shaly, how great their bulk porosity is, and whether they can contain hydrocarbons.

MATERIAL

Available archival material regarding porosity and permeability in the lower Paleozoic strata, from the Lower Cambrian to the Silurian, was collected and compiled for preliminary recognition of the distribution of reservoir parameters. This comprises 114 borehole sections in which 2743 samples were analysed to determine their porosity and 1662 samples were tested to determine permeability. All the measurements were carried out on core samples by laboratories of the Polish Oil and Gas Company onshore, and LOTOS Petrobaltic S.A. Company with the co-operation of the Oil and Gas Institute for the Baltic Sea area.

The irregular distribution of the information collected, with results of tests derived from various laboratories at different times, does not allow us to carry out any reliable statistical analysis and hydrocarbon assessment. For these reasons, evaluation of potential reservoir horizons in the Cambrian strata was based on results of porosimetric measurements on 210 samples from 18 boreholes (Tables 1 and 2). Owing to fairly representative data, the analyses were carried out for rocks of the *Paradoxides paradoxissimus* Superzone and the *Eccaparadoxides oelandicus* Superzone.

To evaluate petrophysical parameters of the lower Paleozoic strata, principally of the Middle Cambrian deposits, available results of porosimetric measurements, conducted at the Department of Fossil Fuels, AGH University of Science and Technology, Kraków, was gathered and supplemented with

Table 1

Compilation of mean values of petrophysical parameters in rocks of the *Paradoxides paradoxissimus* Superzone encountered in boreholes

Borehole name	*n*	Apparent (skeletal) density [g/cm^3]	Bulk density [g/cm^3]	Effective porosity [%]	Average capillary diameter [μm]	Total pore area [m^2/g]	Threshold diameter [μm]	Dynamic porosity for gas [%]	Dynamic porosity for oil [%]
A23-1/88	3	2.69	2.62	2.87	0.04	1.33	30.00	1.50	1.20
B4-2A/02	15	2.57	2.41	6.21	0.98	0.19	27.42	5.95	4.39
B6-1/82	32	2.61	2.36	9.44	1.06	0.38	14.38	9.00	6.96
B2-1/80	6	2.63	2.54	3.73	0.19	0.43	15.00	3.27	1.20
B3-1/81	15	2.50	2.31	13.76	0.75	0.67	14.63	6.44	4.46
B4-1/81	14	2.57	2.39	7.31	0.37	0.66	14.64	6.79	5.46
B6-2/85	15	2.63	2.50	7.34	0.43	0.64	15.07	6.79	4.79
B7-1/91	9	2.64	2.57	2.70	0.75	0.14	14.33	2.58	1.67
B8-1/83	14	2.57	2.43	5.61	0.99	0.42	16.16	5.05	3.74
B16-1/85	15	2.66	2.53	4.69	0.17	0.75	8.99	3.85	1.44
Hel IG 1	19	2.63	2.54	3.71	0.14	0.56	14.73	3.10	1.24

n – number of samples

Table 2

Compilation of mean values of petrophysical parameters in rocks of the *Eccaparadoxides oelandicus* Superzone encountered in boreholes

Borehole name	*n*	Apparent (skeletal) density [g/cm^3]	Bulk density [g/cm^3]	Effective porosity [%]	Average capillary diameter [μm]	Total pore area [m^2/g]	Threshold diameter [μm]	Dynamic porosity for gas [%]	Dynamic porosity for oil [%]
A8-1/83	2	2.52	2.49	1.25	0.74	0.03	100.00	1.05	0.5
B2-1/80	5	2.64	2.56	3.04	0.15	0.33	22.20	2.66	0.7
B3-1/81	1	2.72	2.44	10.00	0.06	2.69	0.20	5.00	1.2
B4-1/81	1	2.66	2.48	6.60	0.05	2.08	6.00	2.10	1.5
B7-1/91	5	2.60	2.43	6.48	0.21	0.57	0.90	5.52	1.62
Hel IG 1	2	2.68	2.55	4.95	0.07	1.22	15.15	2.95	0.3

Explanations as in Table 1

samples from the newest offshore boreholes. The material comprises porosimetric measurement results from the following boreholes: A8-1/83, A23-1/88, B4-2A/02, B6-1/82, B2-1/80, B3-1/81, B4-1/81, B6-2/85, B7-1/91, B8-1/83, B16-1/85, Hel IG 1, Dębki 3, Dębki 4, Dębki 5K, Żarnowiec 7, Żarnowiec 8K and Żarnowiec 9K (Tables 1 and 2; Fig. 1).

EVALUATION OF PETROPHYSICAL PARAMETERS OF THE PORE SPACE IN BOREHOLES OF THE PALEOZOIC STRATA

The Cambrian rocks were identified on the basis of characteristic anomalies on well logs. The *Paradoxides paradoxissimus* Superzone and *Eccaparadoxides oelandicus* Superzone distinguished in boreholes that penetrated the full thickness of the Cambrian strata or at least reached them were correlated along three correlation lines comprising the following boreholes: Łeba 8, Białogóra 3, Dębki 3 and Żarnowiec IG 1 (Profile I); A8-1/83, B6-3/02 and B6-1/82 (Profile II); and A23-1/88, B4-2A/02 and B4-1/81 (Profile III; Fig. 1).

The porosimetric measurements show that the Middle Cambrian rocks of the *Paradoxides paradoxissimus* Superzone, recognized in 11 boreholes, are characterized by apparent (skeletal) density ρ_s of 2.50–2.69 g/cm^3, and bulk density ρ_o of 2.31–2.62 g/cm^3. Their average capillary diameter Φ ranges from 0.4 to 1.06 μm. Their total pore area *S* ranges from 0.14 to 1.33 m^2/g and the threshold diameter φ ranges from 8.99 to 30 μm (Table 1). As a consequence of the petrophysical parameters obtained, their effective porosity ranges from 2.87% in the A23-1/88 borehole section to 13.76% in the B3-1/81 borehole section. Dynamic porosity for gas varies from 1.50% in A23-1/88 to 9.0% in B6-1/82, whereas for oil it varies from 1.20% in A23-1/88 and B2-1/80 to 6.96% in B6-1/82. The analysis of the distribution of the pore space geometry demonstrates its porous character, within the range of capillary and subcapillary pores, as well as its porous-fractured and fractured character (Figs. 2 and 3).

The *Eccaparadoxides oelandicus* Superzone was encountered in 6 boreholes. The rocks are characterized by variable apparent (skeletal) density ρ_s within the range of 2.52–2.72 g/cm^3, and bulk density from 2.44 to 2.56 g/cm^3. The average capillary

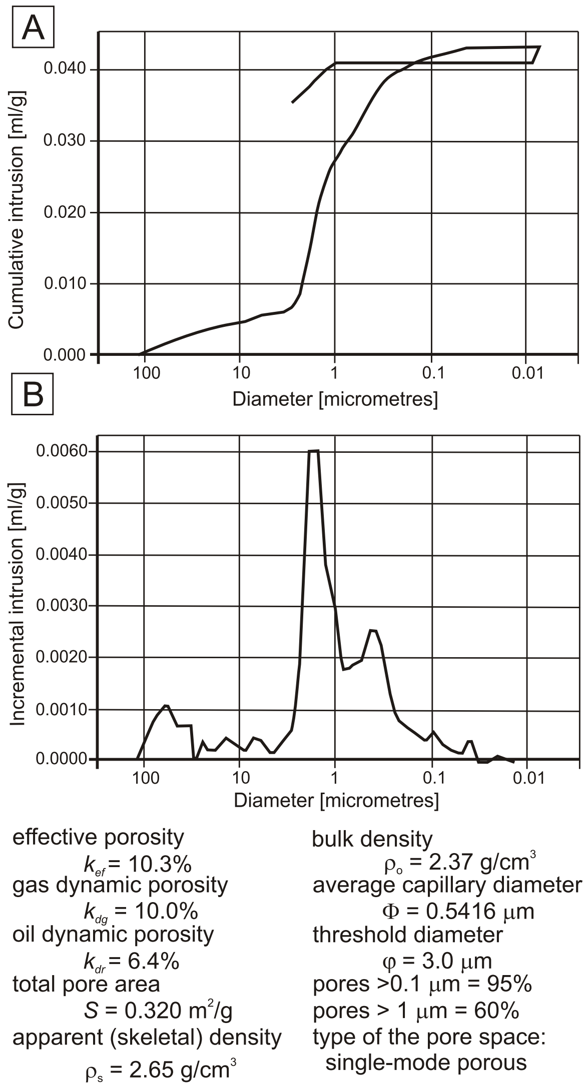


Fig. 2. Mercury porosimetry results

A – cumulative intrusion; **B** – incremental intrusion *versus* diameter from porosimetric investigations of rocks of the Middle Cambrian *Paradoxides paradoxissimus* Superzone in the B6-1/82 borehole at a depth of 1478.4 m

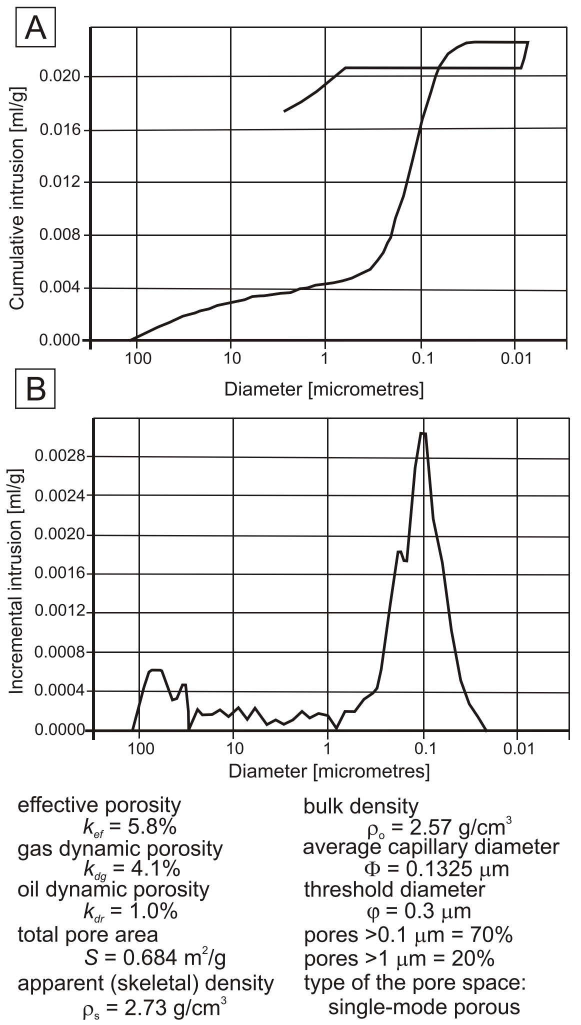


Fig. 3. Mercury porosimetry results

A – cumulative intrusion; **B** – incremental intrusion *versus* diameter from porosimetric investigations of rocks of the Middle Cambrian *Paradoxides paradoxissimus* Superzone in the B4-2A/02 borehole at a depth of 1157.2 m

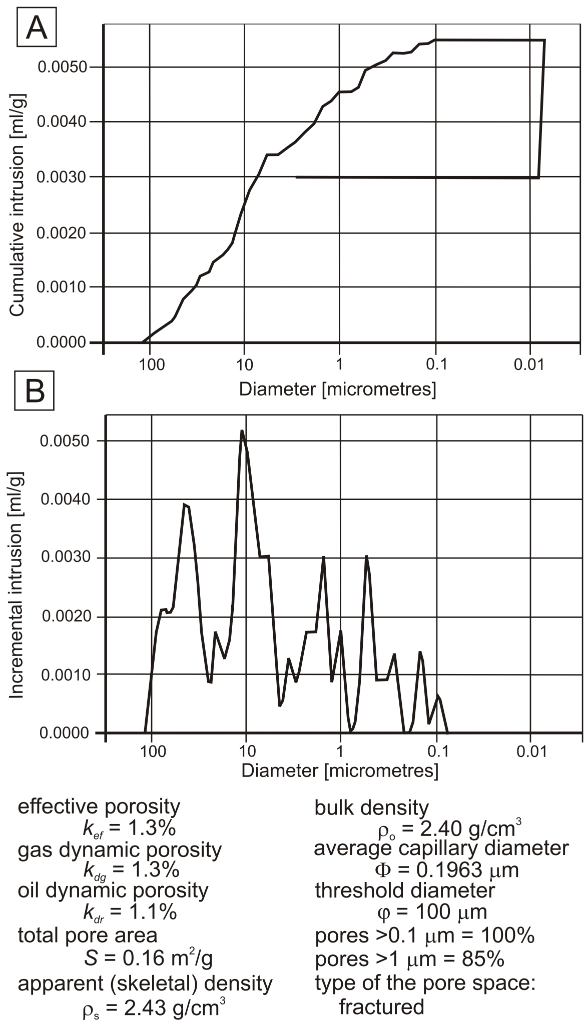


Fig. 4. Mercury porosimetry results

A – cumulative intrusion; **B** – incremental intrusion *versus* diameter from porosimetric investigations of rocks of the Middle Cambrian *Eccaparadoxides oleandicus* Superzone in the A8-1/83 borehole at a depth of 1964.6 m

diameter Φ ranges from 0.07 to 0.74 µm, total pore area S ranges from 0.3 to 2.69 m^2/g, and threshold diameter φ varies widely from 0.20 µm in a single sample up to 100 µm in two non-representative samples (Table 2). The effective porosity ranges from 1.25% in the A8-1/83 boreholes to 10.00% in the B3-1/81 borehole, the dynamic porosity for gas varies from 1.05% in A8-1/83 to 5.52% in B7-1/91, and for oil – from 0.30% in the Hel IG 1 borehole to 1.62% in the B7-1/91 borehole. These deposits are characterized by mostly fractured reservoir space (Fig. 4).

The Upper Cambrian strata (encountered in the Dębki 4 and Dębki 5K boreholes), which have the petrophysical parameters presented, represent a reservoir rock type with very low capacity and complex porous, porous-fractured, and fractured pore spaces.

Non-representative, individual results of porosimetric measurements in the Lower Cambrian Żarnowiec Formation of the *Mobergella* Zone and *Holmia* Zone do not enable us to qualify them from the point of view of potential reservoir rock occurrence, and their reservoir space type corresponds to fractured rocks (Figs. 5–7).

ANOMALIES ON WELL LOGS AS A SOURCE OF SUPPLEMENTARY INFORMATION ON RESERVOIR PROPERTIES OF THE CAMBRIAN ROCKS

Distinct anomalies on well logs have confirmed the correctness of the stratigraphic divisions, particularly in the Cambrian formations (Tables 3–5). For boreholes in which Cambrian rock samples were analysed in the laboratory, values of the laboratory-tested effective porosity (PHIE) were plotted onto the well logs. Part of the horizons correlated within Ordovician, Cambrian, and Precambrian sequences along the line comprising boreholes: Łeba 8–Białogóra 3–Dębki 3–Żarnowiec IG 1 is depicted in Figure 8. Table 3 presents depths to the top of the horizons correlated within the Cambrian interval along this line.

Sandstones of the *Paradoxides paradoxissimus* Superzone, with a small proportion of claystone intercalations, represent an oil-saturated reservoir horizon in all boreholes. On well logs this

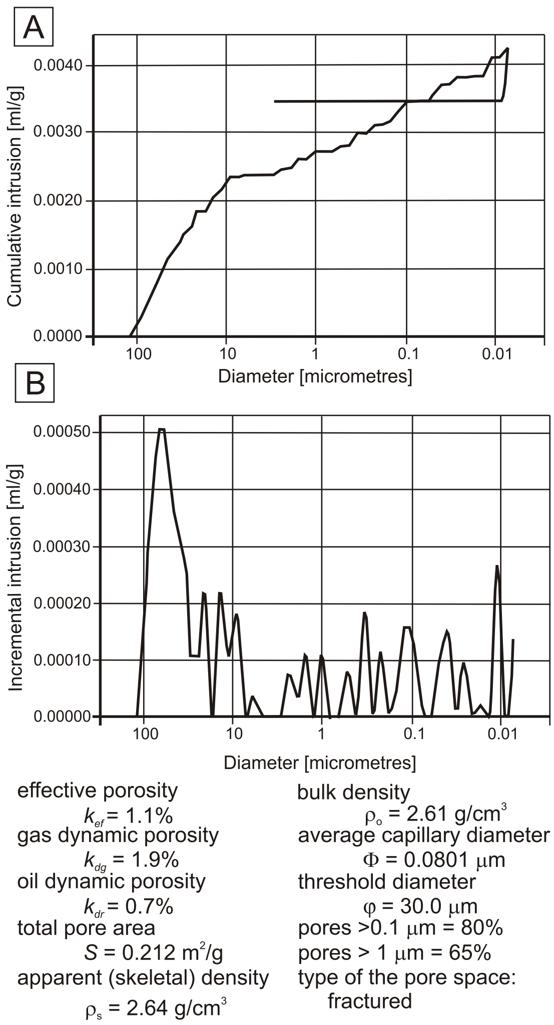


Fig. 5. Mercury porosimetry results

A – cumulative intrusion; **B** – incremental intrusion *versus* diameter from porosimetric investigations of rocks of the Lower Cambrian *Mobergella* Zone in the A23-1/88 borehole at a depth of 1534.9 m

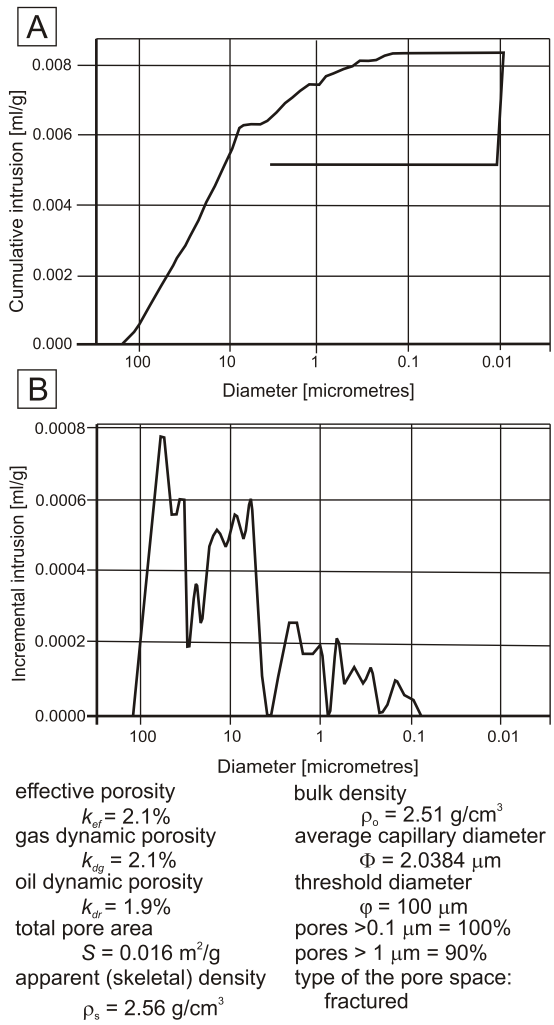


Fig. 6. Mercury porosimetry results

A – cumulative intrusion; **B** – incremental intrusion *versus* diameter from porosimetric investigations of rocks of the Lower Cambrian *Holmia* Zone in the A8-1/83 borehole at a depth of 2103.3 m

horizon is marked by decreased natural radioactivity (GR) in all boreholes that penetrated the Cambrian strata. On the neutron-gamma log, distinct differentiation of values (NEGR) in the Białogóra 3, Dębki 3, and Żarnowiec IG 1 boreholes can be observed. Results of the NEGR logs are expressed in pulses per minute, thus the decreased values of anomalies mean enhanced neutron porosity, which can also result from increased clay content. The amplitudes of anomalies on well logs are influenced by borehole diameter. It was recorded that changes of the borehole diameter in the Cambrian strata of the Łeba 8 and Dębki 3 boreholes caused decrease in the anomaly values. In general, the well logs have confirmed the sandy character of the *Paradoxides paradoxissimus* Superzone. The underlying *Eccaparadoxides oelandicus* Superzone represents a sealing horizon which, compared to the *Paradoxides paradoxissimus* Superzone, is characterized by increased anomalies on GR and even more decreased NEGR values, decreased electrical resistivity, and increased borehole diameter as compared to a nominal value. This zone is composed of claystones, siltstones, and shaly sandstones. In the latter case, the decrease in the NEGR (neutron porosity) results from the shaliness of this zone (Fig. 8).

The Upper Cambrian deposits resting above the *Paradoxides paradoxissimus* Superzone are characterized by small thicknesses: from 9.6 m in the Żarnowiec IG 1 borehole to 16 m in the Dębki 3 borehole. Upwards in the deposits, increased values on the GR log can be observed in all boreholes, which corresponds to increased shaliness. The A8-1/83 and B6-1/82 boreholes reached the Precambrian basement whereas the B6-3/02 reached the *Eccaparadoxides oelandicus* Superzone (Fig. 9). Well logs that illustrate the Cambrian lithology in A8-1/83 and B6-1/82 demonstrate different anomalies. The Proterozoic strata are visible on well logs thanks to increased natural radioactivity, lower interval transit time, increased bulk density, increased apparent resistivity, and decreased neutron porosity compared to the overlying Żarnowiec Formation (Lower Cambrian–Vendian). The Cm2 *p.p.* Superzone in boreholes A8-1/83, B6-3/02 and B6-1/82 (Table 4) is characterized by lower GR, RHOB and NPHI indications in comparison with the underlying and overlying deposits (Fig. 9). Anomalies observed on log curves allowed us to assume that this zone is composed of sandstones with a low content of clay minerals and enhanced bulk porosity; they are saturated with hydrocarbons and in the bottom part with formation water.

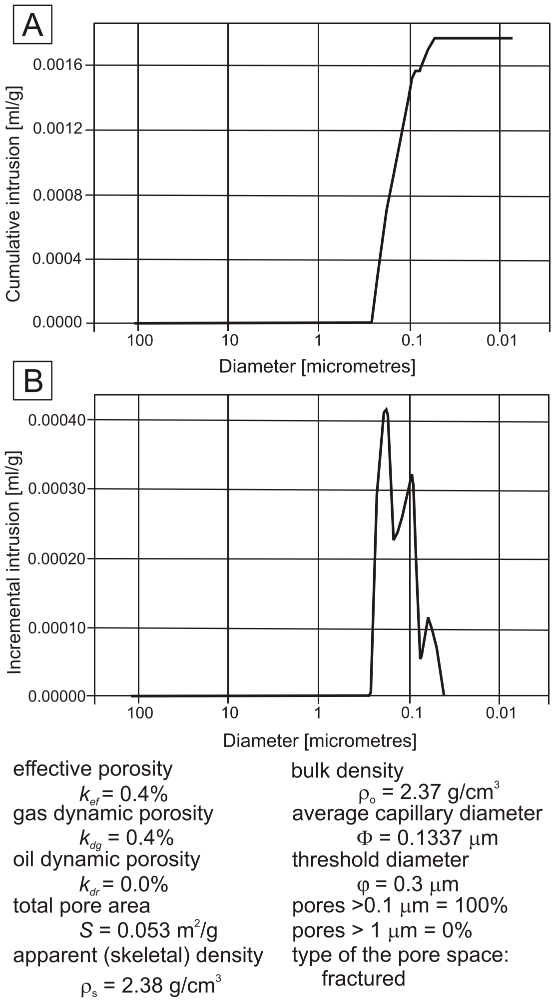


Fig. 7. Mercury porosimetry results

A – cumulative intrusion; **B** – incremental intrusion *versus* diameter from porosimetric investigations of rocks of the Lower Cambrian Żarnowiecka Formation in the A23-1/88 borehole at a depth of 1689.2 m

Their effective porosity is small (from 1.2 to 2.2%), and their pore space character, determined as fractured, ranged within the subcapillary and capillary space interval (from 0.04 to 100 µm); this has confirmed the low contents of clay minerals (Fig. 9). The underlying and overlying sealing horizons (Cm2 *e.o.* and Cm3, respectively) are represented by rocks with high content of clay minerals. In the Upper Cambrian strata, the highest intensity of natural radioactivity was recorded.

In the A23-1/88, B4-2A/02, and B4-1/81 boreholes, Cambrian, Ordovician, Silurian, and Quaternary deposits were encountered. The Lower Cambrian of the A23-1/88 and B4-1/81 boreholes is developed as deposits of the Żarnowiec Formation, and the *Mobergella*, *Holmia* and *Protolenus* zones (Table 5 and Fig. 10). The Middle Cambrian of the three boreholes is represented by deposits of the *Eccaparadoxides oelandicus* Superzone and the *Paradoxides paradoxissimus* Superzone, and in the A23-1/88 borehole also by the *Paradoxides Forchhammeri* Superzone. Cambrian rocks of the latter superzone are characterized by low porosity (from 1.99 to 4.4%). They are fractured rocks with fracture widths from 0.01 to 30 µm, thus representing the capillary and subcapillary pore sizes. Reservoir deposits of the *Paradoxides paradoxissimus* Superzone are characterized by a decrease in GR and decreased interval transit time. In the upper part of this superzone, increased apparent resistivity was recorded (boreholes B4-2A/02 and B4-1/81), whereas the apparent resistivity decreases in the lower part. This can be noticed on the induction log (ILD) and the normal electric resistivity log (EN16). Wireline logging results, together with data on porosity, saturation and lithology for the B4-1/81 borehole, are illustrated in Figure 10. Enhanced porosity and a high proportion of the sandy constituent can be observed in the *Paradoxides paradoxissimus* Superzone. In general, it can be stated that the Cm2 *p.p.* Superzone represents a sandy reservoir with enhanced bulk porosity, saturated with hydrocarbons. This superzone was investigated in detail in the A23-1/88 boreholes.

Rocks of the *Paradoxides paradoxissimus* Superzone are typified by variable effective porosity, from 1.9 to 4.4% (mean 2.87%). The character of the pore space represents the fractured type with fracture width from 0.01 to 30 µm. Then, deposits of this superzone in the boreholes analysed can be classified among fractured reservoir rocks with very low capacities (Figs. 2 and 3).

Rocks of the *Mobergella* Zone show effective porosity from 1.1 to 1.9%. The porosities and contribution of fractures (from 0.01 to 40 µm in width) to the rock texture classify these among fractured reservoir rocks with very low capacities for oil and gas (Fig. 5).

The sealing horizon is formed by deposits of the *Eccaparadoxides oelandicus* Superzone, developed mostly as claystones and siltstones. They correspond to increased values of natural radioactivity (GR) and interval transit time (DTM) recorded in the uppermost part of this superzone (in the B4-1/81 borehole). Above the reservoir horizon of the

Table 3

Depth to top of horizons correlated along the profile Łeba 8–Białogóra 3–Dębki 3–Żarnowiec IG 1

Stratigraphic division			Borehole horizon	Łeba 8	Białogóra 3	Dębki 3	Żarnowiec IG 1
				Depth of the horizon top [m]			
CAMBRIAN	Upper		Cm3	2735.0	2670.0	2673.5	2716.8
	Middle	*Paradoxides paradoxissimus (p.p.)* Superzone	Cm2 *p.p.*	2746.5	2684.0	2689.5	2726.4
		Eccaparadoxides oelandicus (e.o.) Superzone	Cm2 *e.o.*	2882.0		2791.6	2824.1
	Lower		Cm1	2992.5			3000.0
		Protolenus (p.) Zone	Cm1 *p.*	2992.5			
		Holmia (h.) Zone	Cm1 *h.*	3028.0			3000.0
		Mobergella (m.) Zone	Cm1 *m.*	3147.0			3110.0

Table 4

Depth to top of horizons correlated along the profile A8-1/83–B6-3/02–B6-1/82

Stratigraphic division			Borehole horizon	A8-1/83	B6-3/02	B6-1/82
				Depth of the horizon top [m]		
CAMBRIAN	Upper		Cm3	1931.0	1418.8.0	1416.5
	Middle	*Paradoxides paradoxissimus* (*p.p.*) Superzone	Cm2 *p.p.*	1945.5	1439.0	1436.5
		Eccaparadoxides oelandicus (*e.o.*) Superzone	Cm2 *e.o.*	2007.0	1510.0	1509.0
	Lower	*Protolenus* (*p.*) Zone + *Holmia* (*h.*) Zone	Cm1 *p.+h.*			1666.0
		Holmia (*h.*) Zone	Cm1 *h.*	2105.0		
		Mobergella (*m.*) Zone	Cm1 *m.*	2146.0		1737.5

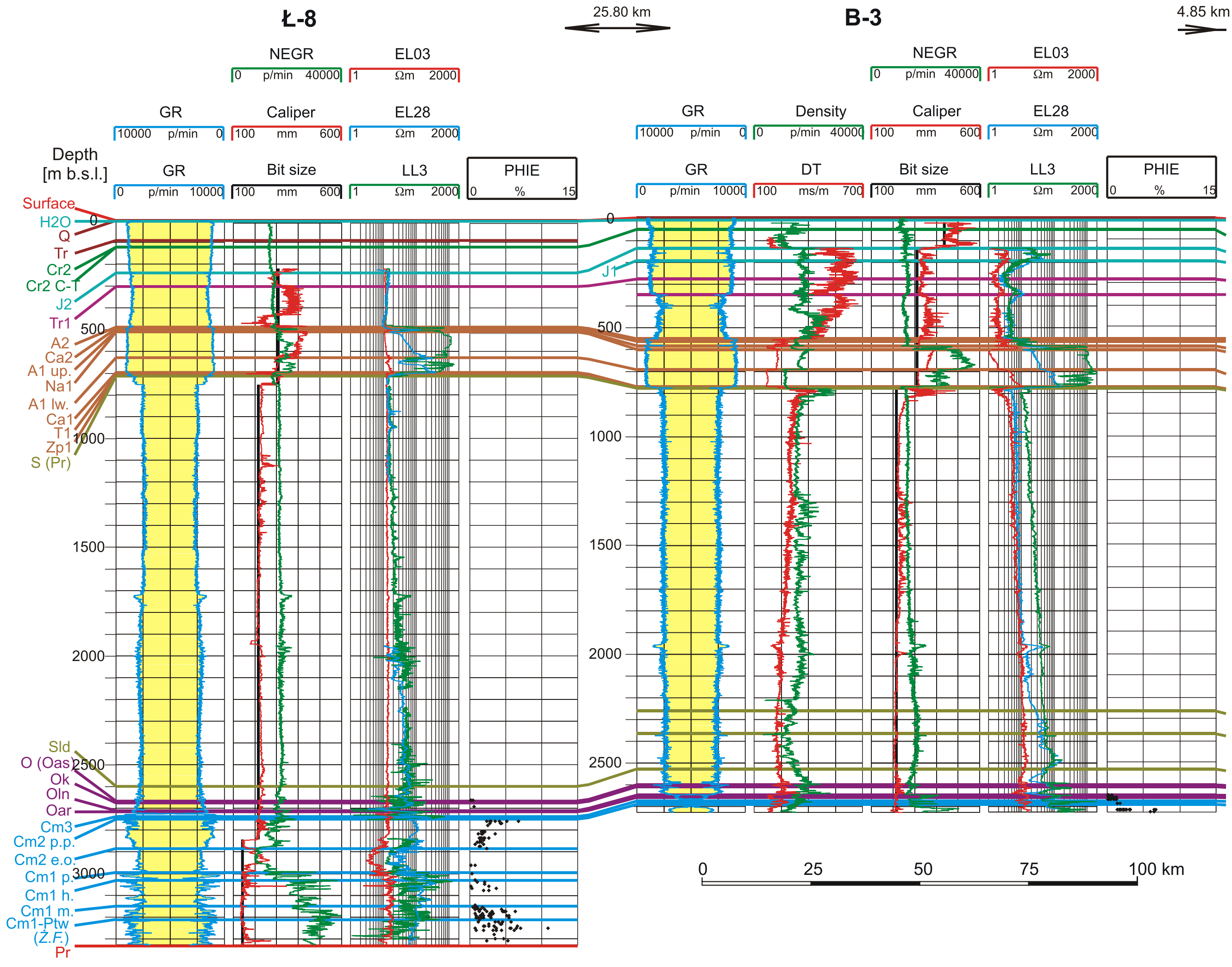


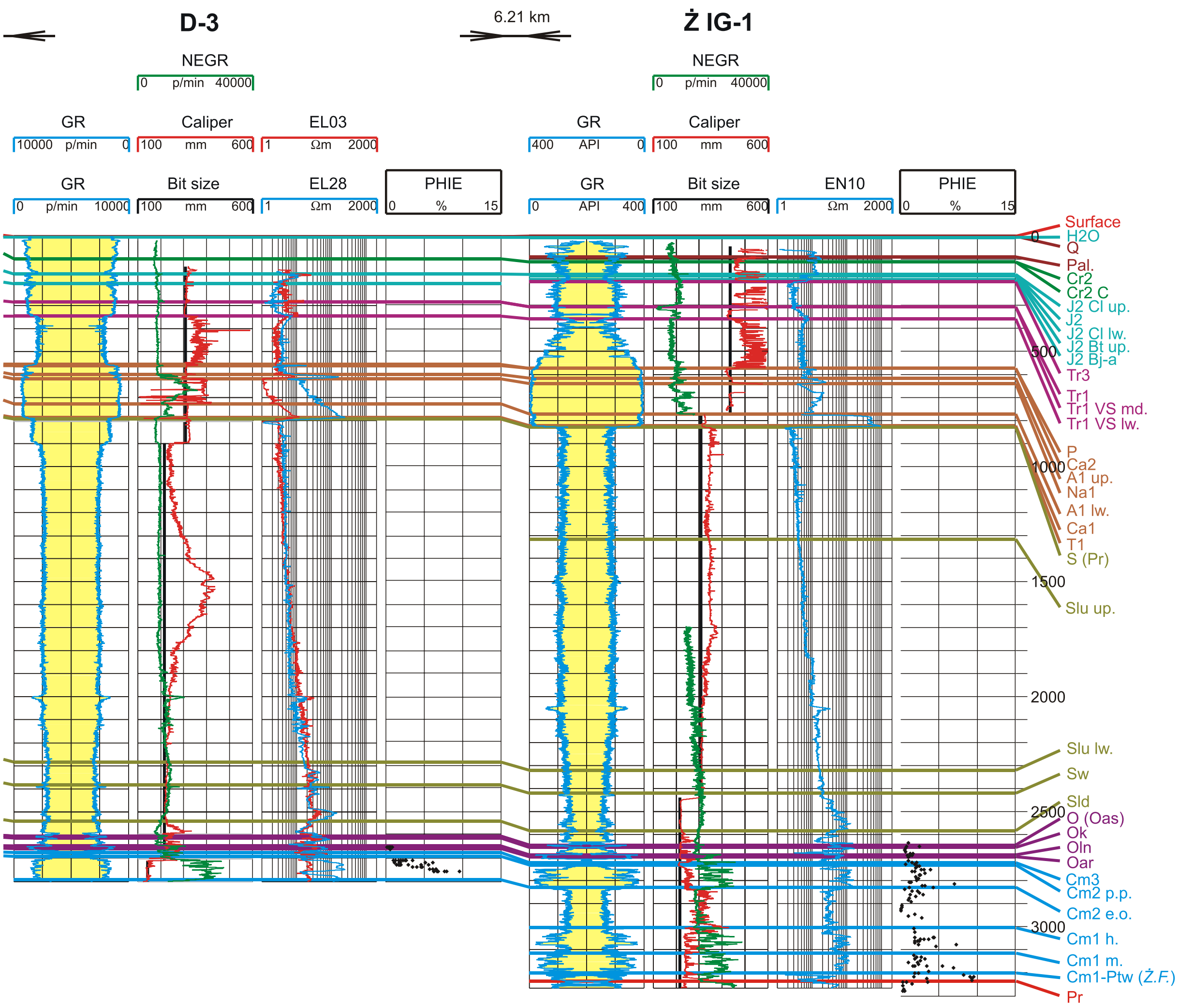
Fig. 8. Correlation of the strata distinguished in the Łeba 8, Białogóra 3,

H2O – sea water level; Q – Quaternary; Tr – Tertiary; Pal. – Paleogene; Cr2 – Upper Cretaceous; Cr2 C – Upper Cretaceous, Cenomanian; Cr2 C-T – Callovian; J2 Bt up. – Middle Jurassic, upper Bathonian; J2 Bj-a – Middle Jurassic, lower land series; Tr3 – Upper Triassic, Tr1 – Lower Triassic; Tr1 VS Ca2 – Main Dolomite: A1up. – Upper Anhydrite, Na1 – Oldest Salt; A1lw. – Lower Anhydrite; Ca1 – Zechstein Limestone; T1 – Copper Shale; Zp1 – Sld – Silurian (Llandovery); O (Oas) – Ordovician (Ashgillian); Ok – Ordovician (Caradocian); Oln – Ordovician (Llanvirnian); Oar – Ordovician *oelandicus*); Cm1 *p.* – Lower Cambrian (*Protolenus*); Cm1 *h.* – Lower Cambrian (*Holmia*); Cm1 *m.* – Lower Cambrian (*Mobergella*); Cm1-Ptw (*Ż.F.)* – log [pulse/minute]; DT – transit interval time [microsecond/meter]; Caliper – borehole diameter log [mm]; Bit size – nominal borehole diameter log [mm]; porosity (effective) from core [%]

Table 5

Depth to top of horizons correlated along the profile A23-1/88–B4-2A/02–B4-1/81

Stratigraphic division			Borehole horizon	A23-1/88	B4-2A/02	B4-1/81
				Depth to top of the horizon [m]		
CAMBRIAN	Upper		Cm3	1305.5		1107.0
	Middle	*Paradoxides forchhammeri* (*p.f.*) Superzone	Cm2 *p.f.*	1315.6		
		Paradoxides paradoxissimus (*p.p.*) Superzone	Cm2 *p.p.*	1316.0	1125.5	1109.5
		Eccaparadoxides oelandicus (*e.o.*) Superzone	Cm2 *e.o.*	1410.5	1178.0	1167.5
	Lower	*Protolenus* (*p.*) Zone	Cm1 *p.*	1492.0		
		Holmia (*h.*) Zone	Cm1 *h.*	1514.0		
		Protolenus (*p.*) Zone + *Holmia* (*h.*) Zone	Cm1 *p.*+*h.*			1304.0
		Mobergella (*m.*) Zone	Cm1 *m.*	1591.5		1378.0



Dębki 3 and Żarnowiec IG 1 boreholes (Profile I)

Upper Cretaceous, Cenomanian–Turonian; J2 – Middle Jurassic; J2 Cl up. – Middle Jurassic, upper Callovian; J2 Cl lw. – Middle Jurassic, lower
md.– Lower Triassic, Middle Variegated Sandstones; Tr1 VS lw. – Lower Triassic, Lower Variegated Sandstones; P – Permian; A2 – Basal Anhydrite;
Basal Conglomerate; S(Pr) – Silurian (Pridoli), Slu up. – Silurian, Ludlow: Ludfordian; Slu lw. – Silurian, Ludlow: Gorstian; Sw – Silurian, Wenlock;
(Arenigian), Cm3 – Upper Cambrian; Cm2 *p.p.* – Middle Cambrian (*Paradoxides paradoxissimus*); Cm2 *e.o.* – Middle Cambrian (*Eccaparadoxides*
Lower Cambrian, upper Wend, Żarnowiec Formation; Pr – Proterozoic; GR – gamma ray, natural radioactivity log [pulse/ minute, API]; Density – gamma-gamma
NEGR – neutron porosity log [pulse/minute]; EL03 and EL28 – lateral electric logs, short and long, respectively [ohmm]; LL3 – laterolog [ohmm]; PHIE –

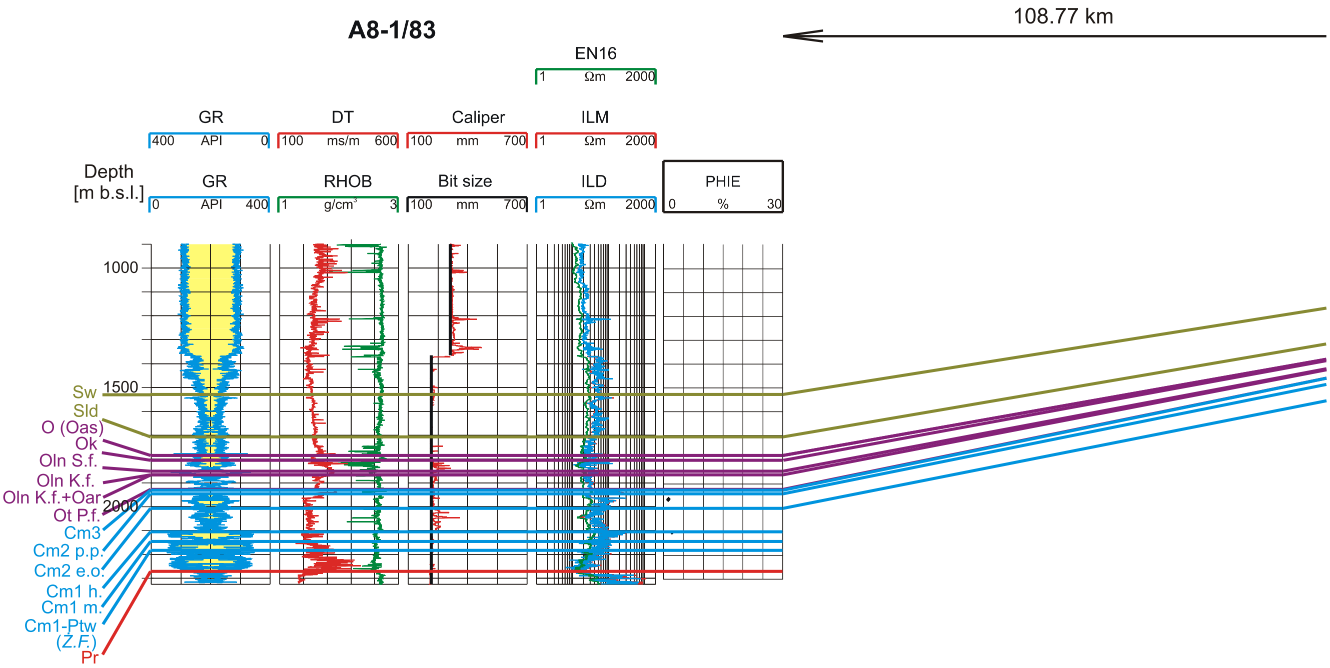


Fig. 9. Logs in the A8-1/83, B6-3/02 and B6-1/82

Oln S.f. – Ordovician, Llanvirnian, Sasino Formation; Oln K.f. – Ordovician, Llanvirnian, Kopalino Formation; Oar K.f. – Ordovician, Arenigian, Kopalino ILM and ILD – induction logs, middle and deep, respectively [ohmm]; EN16 – short normal electric log [ohmm]; NPHI and NPHI(SNP) – neutron porosity

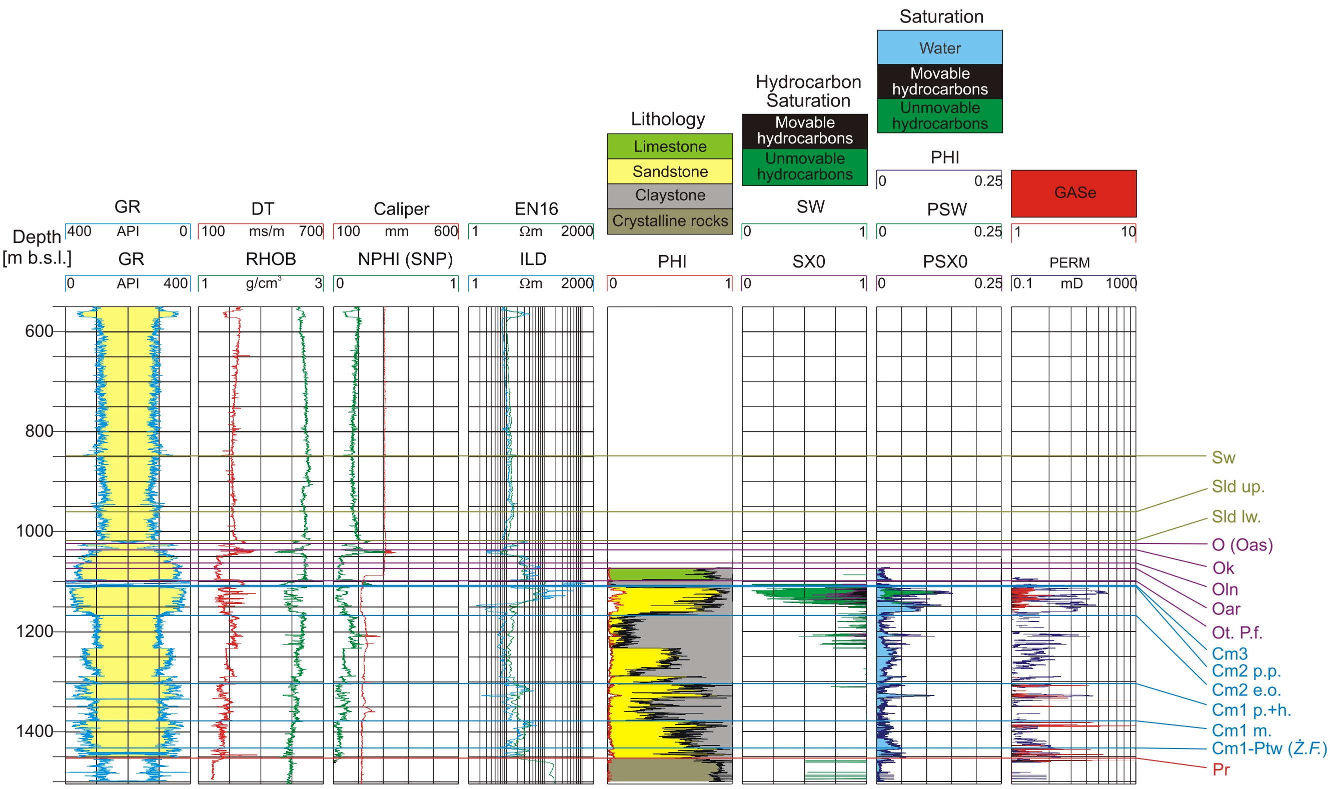
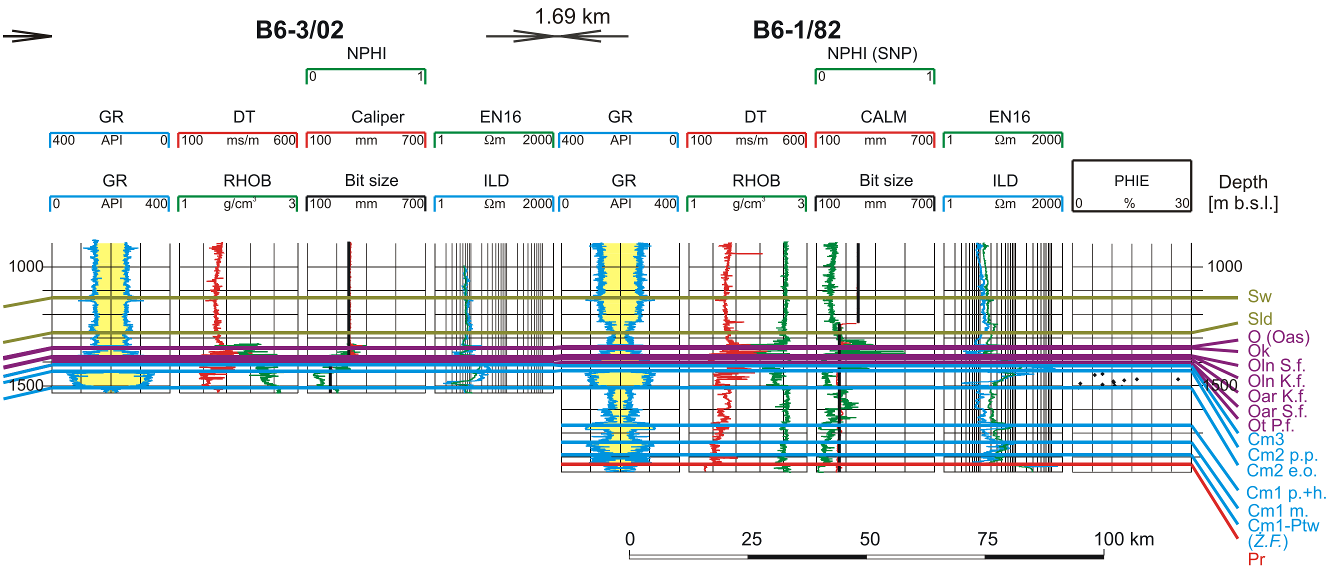


Fig. 10. Logs and results of the comprehensive interpretation of the B4-1/81 borehole (Profile III)

Sld up – Silurian, upper Llandovery, Sld lw – Silurian, lower Llandovery; SW – water saturation in virgin zone; SX0 – water saturation in flushed zone; PHI – porosity [dec.]; PSW – volume of rock occupied by water in virgin zone [dec.]; PSX0 – volume of rock occupied by water in flushed zone[dec.]; PERM – permeability [mD]; other explanations as in Figure 8



boreholes in the Cambrian section (Profile II)

Formation; Oar S.f. – Ordovician, Arenigian, Słuchowo Formation; Ot P.f. – Ordovician, Tremadocian, Piaśnica Formation; RHOB – bulk density [g/cm^3]; [dec.], other explanations as in Figure 8

Paradoxides paradoxissimus Superzone, Upper Cambrian and Tremadocian deposits occur, which reveal high indications on the GR log, and increased apparent resistivity, interval transit time and neutron porosity. The Upper Cambrian is represented by claystones with limestone interbeds.

The correlation of the beds identified shown in the boreholes depicts the occurrence of the Cambrian deposits with strong emphasis on the *Paradoxides paradoxissimus* and *Eccaparadoxides oelandicus* superzones which are important from the point of view of hydrocarbon accumulation and production. Towards the A23-1/88 borehole, descending tops of particular horizons can be observed. The anomalies described on well logs constitute the basis for selection of reservoir horizons in the formations studied, which were subsequently analysed in detail to determine their petrophysical parameters.

PETROPHYSICAL PARAMETERS OF THE *PARADOXIDES PARADOXISSIMUS* SUPERZONE AND OF THEIR MUTUAL RELATIONSHIPS

Considering the number of the samples analysed and the results obtained that indicate their anisotropy, to evaluate the mutual relationships only the Middle Cambrian rocks representing the *Paradoxides paradoxissimus* Superzone were subjected to statistical analysis. The statistical distribution of the effective porosity values for the whole population of the samples analysed with reference to distinguished facies reveals features of a normal distribution. Reservoir rocks with very low and low capacities have the largest contribution equal to 79%; there are 16% of rocks with moderate capacity and 6% of rocks with high and very high capacity (Fig. 11A). The distribution of dynamic porosity values for gas is similar, where reservoir rocks with very low and low capacities are predominant (84%). The contribution of reservoir rock samples with moderate and high capacities is lower and equals 13 and 5%, respectively (Fig. 11B). When the zone is evaluated as a reservoir rock for oil, a characteristic feature is the proportion of pores with very low and low capacities that amounts to 86%; moderate-capacity pores represent 10% and high-capacity pores only 2% of all the samples (Fig. 11C).

All the petrophysical parameters that characterize the physical properties of rocks should correlate mutually from the very nature of things, thus allowing one to statistically predict their values. Of course, this statement concerns an ideal, and at least homogeneous, porous medium.

To evaluate the distribution of petrophysical parameters in the *Paradoxides paradoxissimus* Superzone the authors made an effort to find relationships between particular petrophysical parameters that characterize the physical properties of this zone. All departures from observed trends would be caused by a variability of facies model (Modliński and Podhalańska, 2010) and particularly by diversified systems of fractures, which are so numerous in this reservoir horizon.

From a number of petrophysical parameters that result from the accepted investigation methodology, to find correlation relationships the authors used values of the following physical quantities: apparent (skeletal) density, bulk density, average capillary diameter, and total pore area, related to the effective porosity and to the dynamic porosity for gas and oil.

When correlation relationships between effective porosity and other physical parameters are taken into account, an anomalous increase in this porosity with apparent (skeletal) density is worthy of note. This increase seems to be explained by the role of fracture systems which, in great measure, develop in more silicified, homogeneous rock packages of increased specific gravity. This rock type is particularly susceptible to fracturing (Strzetelski, 1980). Bulk density, which from the very defini-

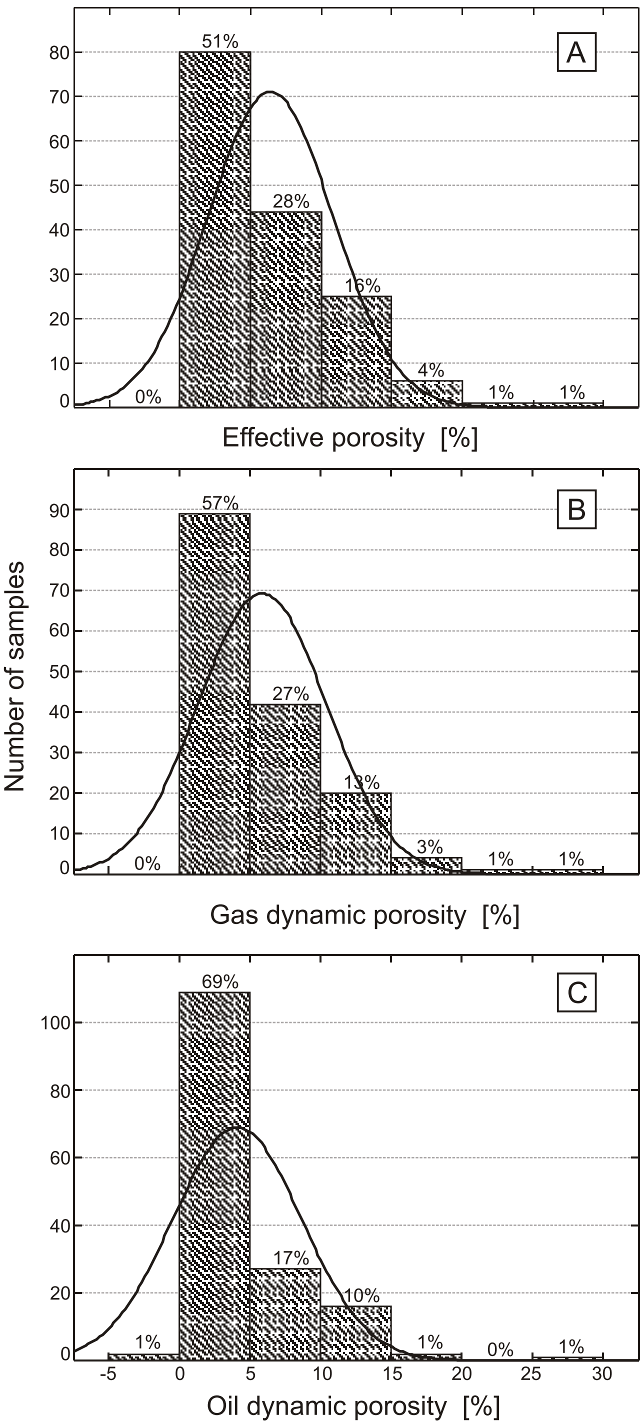


Fig. 11. Statistical distribution of A – effective porosity, B – gas dynamic porosity, C – oil dynamic porosity in rocks of the Middle Cambrian *Paradoxides paradoxissimus* Superzone

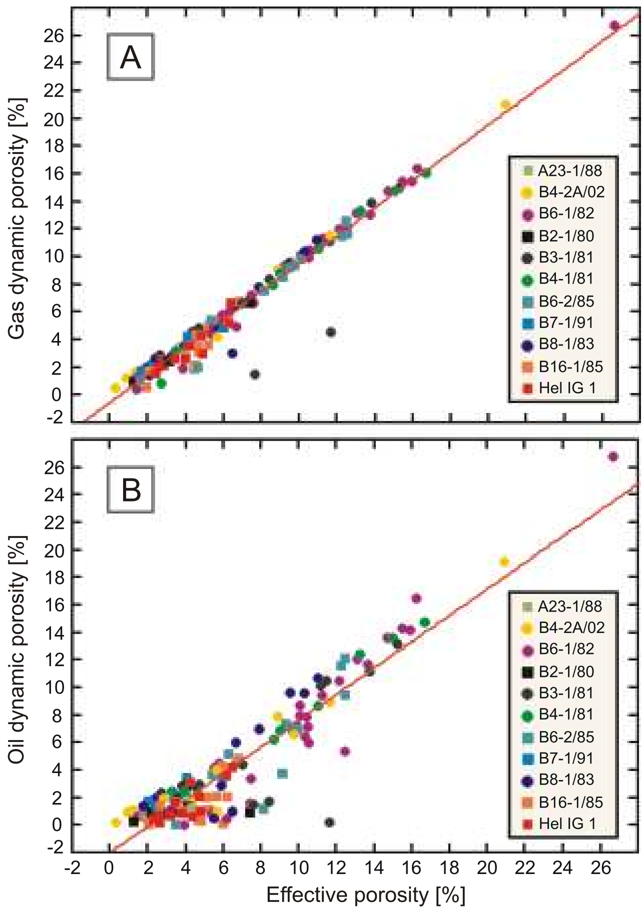


Fig. 12. Relations between dynamic porosity and effective porosity in rocks of the Middle Cambrian *Paradoxides paradoxissimus* Superzone: A – gas, B – oil

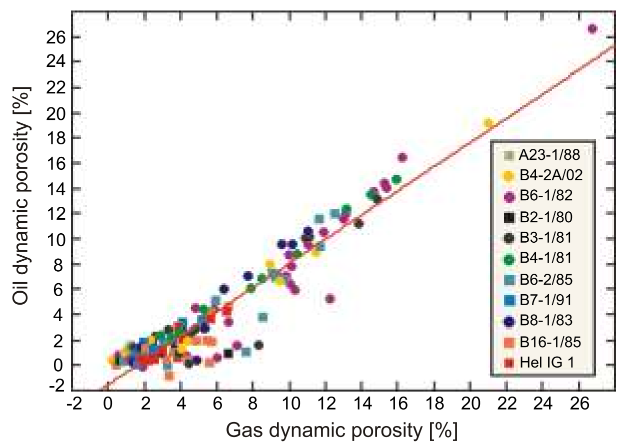


Fig. 13. Oil dynamic porosity *versus* gas dynamic porosity in rocks of the Middle Cambrian *Paradoxides paradoxissimus* Superzone

tion comprises the pore space, demonstrates a relationship between these parameters. Increased values of bulk density, over 2.35 g/cm^3, correspond to rocks classified as having very low and low capacities. A bulk density less than 2.35 g/cm^3 is typical of rocks classified as having moderate, sporadically high capacities.

The increase in effective porosity is undoubtedly related to the increase in average capillary diameter. Except a few cases, which no doubt are connected with the fracturing degree, rocks qualified as having very low and low capacities are related to low values of average capillary diameters, below 1 μm; their importance grows where capillary diameters read on the order of 2 μm, that is already within the interval of increased sizes of capillary pores. In complex porous and fractured reservoir rocks, decreased total pore area at increased effective porosity can be justified. A few samples demonstrate features of porous

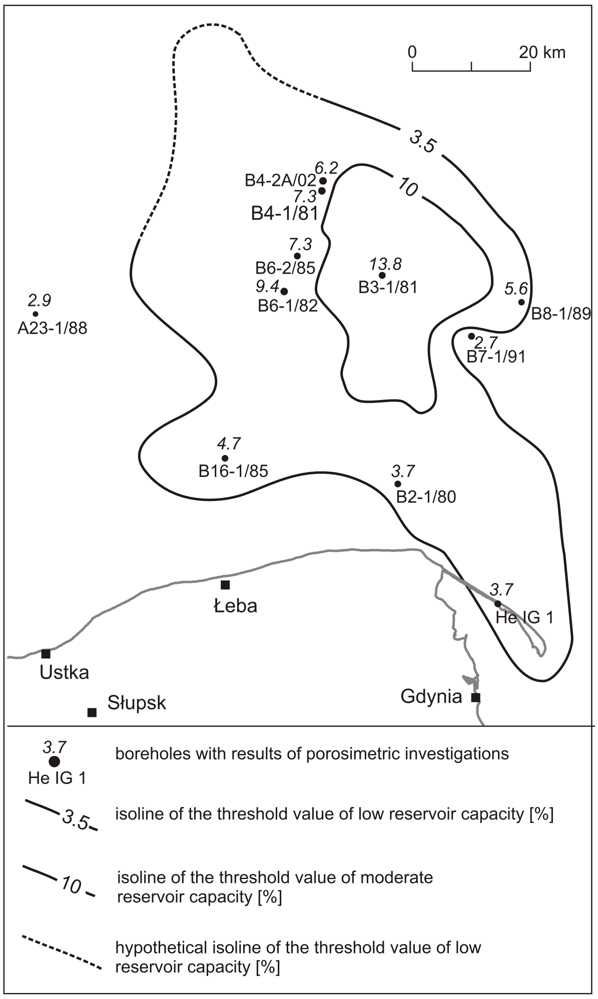


Fig. 14. Sketch map of threshold values of reservoir capacity in the Middle Cambrian deposits

rocks, especially within the interval of pores with small capillary diameters, which at higher values of total pore area (even on the order of 2.5 m^2/g) reveal porosities from 6 to 8% at most. An insignificant decrease in effective porosity with decreasing threshold diameter may seem unjustified. However, it is undoubtedly related to the occurrence of fractures. The connection of high threshold diameter in fractured rocks with their low capacity is revealed here.

Very similar relationships appear with regard to dynamic porosity for gas: the apparent (skeletal) density increase with porosity and the bulk density decrease with this parameter. Average capillary diameter exerts a marked influence on the dynamic porosity for gas: just at the diameter of 1 μm it allows the attainment of porosities higher than 10%. Likewise, increasing porosity with decreasing values of total pore area can be noticed. Anomalously increased values of total pore area at low porosities are indicative of the influence of pore space whereas increased threshold diameters at low porosities show the occurrence of fracture systems.

As far as dynamic porosity for oil is taken into account, the dependence of this parameter on apparent (skeletal) density is still valid, which indirectly indicates the role of rock fracturing. Low values of apparent (skeletal) density related to dynamic porosity indicate the development of a porous reservoir. This complex character of the reservoir space can be confirmed by values of bulk density, which are high at low porosities in the fractured space and low at increased porosities of predominant porous type (Fig. 12). Values of dynamic porosity for oil are a direct consequence of increasing average capillary diameter and decreasing total pore area and threshold diameter. Comparison of the effective porosity with dynamic porosity for gas indicates their distinct identity; in relation to a dynamic porosity for oil equal to 8%, the dynamic porosity for gas decreases down to 6%. This can be confirmed by the mutual relationships between the dynamic porosities for gas and oil, where a porosity of 10% for gas corresponds with a porosity of 8% for oil, or a dynamic porosity of 16% for gas corresponds with a dynamic porosity of 14% for oil (Fig. 13).

The analysis of the petrophysical parameters in the Paleozoic strata in the Polish sector of the Baltic Sea shows that the best reservoir properties are characteristic of the deposits of the Middle Cambrian *Paradoxides paradoxissimus* Superzone. However, they can be classified among rocks with very low, low, or moderate reservoir capacities at most. The best reservoir properties occur in the area around the B3-1/81 borehole where effective porosity exceeds 10% (Fig. 14). A significant feature of the zone analysed is represented by the complex character of its pore space where the fractured and fractured-porous type of the pore space is predominant, apart from the porous type.

CONCLUSIONS

The porosimetric measurements and well logging analysis show the strongly heterogeneous character of the pore space in the Cambrian rocks.

The results of the studies have demonstrated that the deposits of the *Paradoxides paradoxissimus* Superzone should be classified among rocks with very low capacity for gas in the A23-1/88, B2-1/80, B7-1/91 and Hel IG 1 boreholes, and among rocks with low capacity for gas in the remaining boreholes. As regards the capacity for oil, deposits of this zone encountered in the B4-2A/02, B6-1/82, B3-1/81, B4-1/81, B6-2/85, and B8-1/83 boreholes can be classified among reservoir rocks with low capacity, and in the remaining boreholes, among rocks with very low capacity. Analysis of the distribution of the pore space geometry has shown the predominance of complex fractured-porous and simple fractured types, with fewer porous-type rocks.

The petrophysical parameters in deposits of the *Eccaparadoxides oelandicus* Superzone should be treated as approximate because the small amount of tests is poorly representative. However, deposits of this zone in the B3-1/81 and B7-1/91 boreholes can be classified among rocks with low reservoir capacity, with the remaining deposits belonging to the very low capacity class. The values of dynamic porosity for oil clearly indicate the very low capacity class. Qualitatively, pore space analysis has shown its fractured-porous, fractured, and porous character.

The Upper Cambrian deposits encountered in the Dębki 4 and Dębki 5K boreholes represent reservoir rocks with very low capacity and complex porous, porous-fractured, and fractured pore space.

Non-representative, single individual of porosimetric measurement in the Lower Cambrian Żarnowiec Formation of the *Mobergella* Zone and *Holmia* Zone, from the A23-1/88 and A8-1/83 borehole sections, do not allow assessment in terms of potential reservoir rock occurrence.

The analysis of the pore space geometry resulting from the porosimetric measurements, together with the statistical analysis of the measurement results, clearly show the complex pore structure of the Cambrian deposits. The fractured and fractured-porous character of the Cambrian deposits is confirmed by the significant contribution of pores with diameters exceeding 0.1 and 1 μm, which is inadequate for the porosities calculated. The increased reservoir capacity of these deposits with the documented occurrence of porous reservoir rocks is worth attention. The predominance of fractured space seems to be shown also by statistical relationships, with low correlation coefficients, between some petrophysical parameters derived from the porosimetric studies. This particularly concerns the relationship between values of apparent (skeletal) density, total pore area and pore diameters, and effective and dynamic porosities.

The variable anomalies observed on well logs confirm the diversified lithological development and reservoir properties of the Cambrian rocks. The gamma ray logs provide information on clay content and the neutron logs on variable porosity. Anomalies on well logs were the basis for correlation of the Cambrian beds depicted. They also confirm good reservoir parameters of the *Paradoxides paradoxissimus* Superzone and the shaly character of *Eccaparadoxides oelandicus* Superzone.

The results of the studies of the Cambrian deposits have demonstrated features of very poor reservoir rocks of low capacity. This cannot, however, represent the only argument in evaluation of the reservoir rocks. The fact remains that from the point of view of volumes of potential hydrocarbon accumulations their capacity is low, but this is a basic feature of reservoir rocks with fractured and fractured-porous space. The results presented have proven the occurrence of this type of reservoir space, but are limited with respect to microporous space, without regard to macrofractures.

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